April 30, 1891.

Sir WILLIAM THOMSON, D.C.L., LL.D., President, in the Chair.

The Presents received were laid on the table, and thanks ordered for them.

The following Papers were read:—

I. "Cloud Photography conducted under the Meteorological Council at the Kew Observatory." By Lieut.-General R. STRACHEY, R.E., F.R.S., and G. M. WHIPPLE, Superintendent of the Observatory. Received April 23, 1891.

In 1878 the Meteorological Council decided upon undertaking a series of experiments with the view of attempting by means of photography to obtain a record of the height and velocity of the clouds, as indicating the movements of the upper parts of the atmosphere. For this purpose a plain cubical camera was constructed, with its optical axis directed to the zenith, and a number of pictures of clouds were thus obtained. The results were so far satisfactory as to establish the possibility of identifying points in the clouds which would admit of the calculation of their height with considerable precision. But, owing to the small field of view of the lens made use of, it was found that the opportunities of photographing clouds in this manner were of somewhat rare occurrence, and it was therefore decided, on the proposal of Captain Abney, to whom the Meteorological Council is indebted for his valuable advice throughout the course of these experiments, to construct two cameras so arranged as to enable them to be directed to any part of the sky, and thus to photograph clouds in all positions.

For this purpose the cameras were fitted with theodolite mountings, provided with altitude and azimuth circles. The dark slides for carrying the sensitised plates were fitted with glass plates, upon which cross lines indicating the position of the optical axis were etched. These lines were photographed simultaneously with the clouds, and the readings of the divided circles, recorded at the time of exposure, thus supplied the altitude and azimuth of the point of the cloud covered by the intersection of the cross lines at that moment.

From a photographic picture of a series of staves erected at known angular intervals, a scale of angular distances was obtained, by means

of which the azimuth and altitude of any point in the cloud picture could be deduced from those of the intersection of the cross lines.

Arrangements were made for erecting these cameras at the extremities of a base of known length (800 yards), between which an electrical communication was established.

Spring shutters were placed over the lenses, which could be liberated and again closed, at the will of the observer, by the passage of an electric current, so as to expose the plates for any desired interval of time.

Captain Abney also, after numerous trials, devised a suitable formula for an emulsion for coating the plates, as special precautions were found to be necessary in order to obtain good cloud photographs.

Captain Abney thus describes the photographic process he proposed:—"My attention has been once more directed to the best photographic process to employ for the delineation of the clouds, a certain inconvenience having attached to the use of collodion-emulsion, which at first I had not foreseen. I had then recourse to gelatine plates, but the manner in which they are ordinarily prepared induces a sensitiveness which becomes unmanageable, even when a diaphragm with a small aperture is used in the lenses. The great desideratum in the plates appears to be that a small variation in the intensity of the light proceeding from the sky or cloud shall produce a great contrast in the intensity of the developed image. A very rapid plate does not answer for this purpose; hence I tried several modifications. The process which at present has given the best results is as follows:—

"150 grains of bromide of ammonium and 10 grains of iodide of potassium are dissolved in 3 oz. of water, to which 80 grains of Nelson's No. 1 photographic gelatine and 80 grains of Coignet's gelatine have been added. This is dissolved by the aid of heat, and 200 grains of silver nitrate dissolved in $1\frac{1}{2}$ oz. of water are added. The whole is warmed to 100° F. for five minutes, and allowed to set after being poured out in a flat dish. The emulsion thus produced is washed (in the usual manner) from the soluble salts, and is then re-melted and plates coated and dried, as is customary in the gelatine process.

"This formula gives very constant results, and great contrasts of image are obtained by careful development."

The years 1881 to 1884 were passed in working out the details of the arrangements above described, and in 1885, after numerous preliminary trials, it was resolved to erect the two cameras at the Kew Observatory. One was placed on the roof of the Observatory building, and the other on a stand in the Old Deer Park, 800 yards from the other, on the road leading to the Observatory from Richond; and a telegraph cable carrying two insulated copper wires of

low resistance, buried a few inches below the surface of the ground, was laid between the two stands. Switches, attached to telephones as well as to an electric battery, were fixed to these stands, and wires were arranged on the cameras, so that the observers could either communicate with one another, or work the exposing shutters of the two cameras at will.

Operations for the determination of cloud height and motion were then carried out on suitable occasions, as follows :—The two observers, termed for convenience A and B, proceeded to their respective stations, each provided with a box containing half-a-dozen dark slides charged with sensitised plates, and also an adjusted watch. The cameras were set up on the pedestals, levelled, and the connecting wires joined up. Locking plates of peculiar construction were provided, which ensured that the zero points in azimuth of both cameras were exactly directed to the same point of the horizon.

The observer at A, when he saw B had reached his station and placed his camera on the pedestal ready for use, attracted B's attention by means of a flag waved overhead, and directed him through the telephone to set the instantaneous shutter of his camera, setting that of his own camera at A at the same time. A then, making use of the push, sent a current of electricity through the two cameras, which should liberate both shutters at the same instant of time. An enquiry was immediately made through the telephone of B, and, if the reply assured A that the shutters were working satisfactorily, the observers proceeded to the second stage of the observation, which was as follows :—

A carefully examined the sky and, selecting a suitable cloud, directed the sights on his camera towards it, making a convenient setting of the horizontal and vertical circles, which he then read off. He then told B to set his camera to the same azimuth and altitude, and insert a loaded plate-holder in its groove, repeating the circle readings to ensure accuracy, and also at the same time to set his shutter. A, whilst directing B through the telephone, conducted the same series of operations at his own instrument, so that, as soon as B telephoned that he was ready for action, A switched the battery on to the line, and, watching the cloud for a favourable instant, touched the push, whereby the two plates were exposed simultaneously, the instant of the exposure being recorded by both observers in their respective note-books. They then quickly exchanged their plate-holders for others containing fresh plates, and again set the shutters, so that by the time sixty or seventy seconds had elapsed since the first exposure was made they were ready for a second, which was carried out as before under the directions of A, both observers again noting the time. After this, A, having switched on the telephones, enquired of B if he had obtained the two pictures. If the reply was in the affirmative,

he was directed to read both his circles, and to enter the readings, with the times of the two exposures and the numbers of the plate-holders in his book, A doing the same for his own instrument.

Having deposited the plate-holders in the light-tight carrying box, another charged pair were taken, and a fresh cloud in another part of the sky selected, and the operations already detailed were repeated, until the stock of charged holders was exhausted.

The observers then, by means of the telephones, again compared their watches, and noting their differences, if any, sighted their cameras on each other, and read their mutual bearings and altitudes. This was done in order to be sure no displacement had taken place in either the orientation or level of the instruments. They then unlocked the stands, dismounted the cameras, and put them away in the lockers of the pedestals, ready for use on another occasion, conveying the plates to the photographic laboratory for development and subsequent treatment.

From time to time, the empty plate-holders were taken out, the lenses directed to each other, and settings made and circles read with the view of determining the true bearings of the fiducial lines before described, from which the angular position of the cloud-points dealt with were obtained.

On removal of the exposed plates from the holders, the dates of the observation having been written on each of the films in pencil, as well as a register number, development proceeded. This was conducted in a wooden tray with a glass bottom specially adapted to hold four plates. The two A's and two B's forming one set of pictures were usually selected for simultaneous development, in order that the negatives obtained might possess the same degree of intensity. Before hydrokinone became an article of commerce, a solution of pyrogallic acid or sulphate of iron was employed as the developing agent, but, since 1889, Edwards's hydrokinone developer has been employed by preference, as being less liable to produce fogged plates.

Owing to the efforts of the Kew observers being chiefly directed to photographing high cirrus clouds, very careful and slow development was required, to produce satisfactory negatives, and it has been generally necessary to continue the operation for about forty minutes to bring out a successful result. In some cases of very thin filmy cirrus, the so-called mare's tail clouds, the development occupied $1\frac{1}{2}$ hours, before the picture appeared.

For discussion of the photographs, in most cases prints were made of the negatives by the ordinary albuminised paper process.

Various methods of obtaining the heights and velocity of motion of the clouds from the photographs thus made have been attempted. The computation by the ordinary trigonometrical formulæ from the

azimuths and altitudes derived by measurement of a series of points in the clouds, properly identified in the sets of pictures, is very tedious, and a graphical method was suggested by Sir G. Stokes, which, though very ingenious, was found to be troublesome in practice, and was not persevered in.

From the nature of the process employed, the indefinite outlines of the clouds, and their incessant change of form, complicated by the effects of perspective distortion on an irregular and ill-defined surface, it is necessarily impossible to identify cloud-points in the different pictures with much precision or make exact measurements; and approximate results, therefore, are all that can be sought for. The object of the enquiry is chiefly to determine the velocity of movement of clouds at varying heights above the earth's surface and to obtain the heights of those observed at the greatest elevations, which appear as cirrus.

If A and B are the azimuths of any point in a cloud, and Z_a and Z_b the zenith distances, observed respectively at A and B, the ends of the base β, then the distances, measured in a horizontal plane passing through the base, D_a, D_b from A and B respectively of the point vertically under the cloud-point will be

$$D_a = \beta \frac{\sin(B)}{\sin(A-B)}, \qquad D_b = \beta \frac{\sin(A)}{\sin(A-B)},$$

and H, the height of the cloud-point above the horizontal plane passing through the base, will be

$$H = \beta \frac{\sin(B)}{\sin(A-B)\tan Z_a} = \beta \frac{\sin(A)}{\sin(A-B)\tan Z_b}.$$

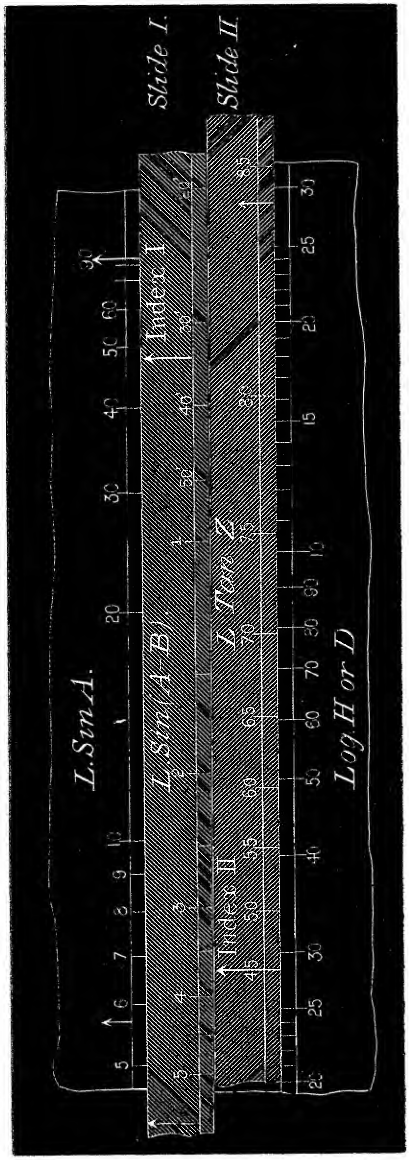
These values are readily found by means of a slide-rule constructed as shown below. The graduations of the upper scale of the fixed rule are log sines; those of the lower scale of the fixed rule logs of numbers, the log of 2400 feet, the length of the base, coinciding with log sin 90°.

The upper sliding rule No. I is graduated with log sines of small angles on the same scale as the first rule, the point marked with index No. I indicating log sine 5° 44′ 27″, which is 9·00000, or 0° 34′ 23″, which is 8·00000.

The lower sliding rule No. II is graduated with log tangents Z, the point marked with index No. II, corresponding to log tan 45°, and on the same scale as the sines.

To apply the rule, bring index No. I of the slide-rule No. I opposite the angle A on the upper fixed scale. Then bring the index No. II of the slide-rule No. II opposite to the angle A—B on the slide-rule No. I.

FIG. 1.



Opposite the index No. II, or tan 45°, will be found on the lower fixed scale the distance D_b, in feet; and opposite to the angle Z_b will be found on the same scale the height of the cloud in feet. By a

similar process will be found the distance D_α and a height of the cloud determined from Z_α.

The position of the point vertically under the selected cloud-point will be determined with sufficient accuracy graphically, by the intersection of the two distances measured from the ends of a line drawn to represent the base.

The repetition of this process for the second set of photographs will in like manner give the position of the cloud-point after the interval elapsed between the taking of the two sets of pictures, and the distance travelled being measured on the diagram, the velocity can be found, and the direction of motion will be shown in relation to the direction of the base.

Irrespective of the laborious nature of this process, it was found that the angles on which it was based were often so small that the results obtained were inconsistent and unreliable.

In 1890, therefore, it was decided to try another method of observing, which would admit of much simpler treatment. This was to fix the cameras so that the optical axes were directed to the zenith, and to photograph clouds which passed across the field of view which is comprised within a circle described at an angular distance of about 15° round the zeniths of the two stations. The defect of this method is that it very materially limited the scope of operations, and reduced the opportunities of taking pictures to a comparatively small number, for it was found that a large proportion of the clouds which seemed apparently favourable for photographing when viewed by reflected solar light incident upon them at oblique angles became almost invisible when observed directly overhead. This was notably the case with cirrus, some forms of which, especially those possessing the nature of cirro-stratus, appear as practically structureless masses when seen in this position. But notwithstanding these drawbacks, some of which, it is hoped, may be obviated, the advantages of this method of observing seem to be sufficient to lead to its adoption in preference to any other yet suggested.

To adapt the cameras for work in this manner, both altitude and azimuth circles were permanently clamped, rendering them immovable in both vertical and horizontal planes, and the locking plates were shifted on the pedestals, so that, while the fiducial lines on the pictures intersect at the zenith, the direction of one of them is that of the line joining the two stations, or the base, the other being at right angles to it.

With the object of ensuring the proper adjustment of the optical axes of the cameras, a tripod stand 12 feet in height was made, which was temporarily erected immediately over them. A plummet was suspended directly above the lens-centre, from the point of intersection of two horizontal wires fixed at right angles to one another, one

of them being carefully made to coincide in direction with the line joining the two cameras.

The charged dark slides, which are separately numbered, so that the correction for each of them may be ascertained and recorded, are then successively placed in the camera and photographs taken of the cross wires overhead, the pictures of which should coincide with the fiducial lines of the camera, the position of which is as nearly as possible adjusted to secure this coincidence. The photographs thus made are preserved, to supply data for correcting the negatives for any error of the fiducial lines, should the slides not be properly adjusted so as to secure the coincidence before spoken of.

Assuming, as may be done without objection for this purpose, that the cloud surface photographed and the earth's surface at the place of observation are in parallel planes, distances measured on the photographs from the intersection of the fiducial lines will represent tangents of angles measured from the zenith to radius equal to the height of the cloud.

Again, if a pair of photographs made simultaneously at the extremities of the base are superimposed one on the other, so that the forms of the clouds coincide, which they will do accurately if the pictures are properly placed, then the line joining the intersections of the cross lines will represent, both in magnitude and direction, the line joining the zeniths of the two ends of the base, from which the observations are made, or the base itself.

If the adjustments before described have been satisfactorily made, the base, as thus indicated, should obviously fall on one pair of the fiducial lines, which, when the photographs are superimposed, should also coincide; otherwise, if the fiducial lines in the two pictures are made to coincide, then the separation of points properly identified in the pictures will be the measure of the parallax or angle subtended by the base at such points.

A scale of angular distance having been prepared as before explained, the parallax thus measured may at once be converted into angular measure, and the height of the cloud is given by the equation

$$H = \beta/\tan \pi,$$

where π is the angular parallax.

In like manner, if two photographs taken from the same point with an interval of time between them be superimposed, so that the cloud pictures coincide, the line joining the intersections of the cross lines will represent in magnitude and direction the movement or drift of the cloud, and the velocity in miles per hour will be found from the equation

$$V = \frac{\delta}{p} \times \frac{\beta}{5280} \times \frac{3600}{t''},$$

where δ and p are the drift and parallax as measured on the photographs, and t the interval in seconds between the pictures being taken.

The method of reduction of the photographs first adopted and employed during the early part of the past summer was as follows :—Prints were made on albuminised paper of the set of four pictures, two taken at each end of the base with an interval of time between them, and they were mounted on stout cards in order to avoid the usual curling up of the paper. When necessary, new fiducial lines were then drawn in the proper direction through the points that had been ascertained to represent the corrected position of the lines of reference as before described, and these lines were extended to the margins of the cards.

If possible, five or six cloud-points were then selected in each print, capable of satisfactory identification. A sheet of paper was next procured, larger than the pictures, and lines intersecting at right angles were drawn across it. Punctures were then made, by means of a needle, through all the selected cloud-points in the four pictures, which were successively placed over the reference sheet (termed hereafter the receiver), so that the fiducial lines upon the pictures coincided with the lines drawn upon the receiver, thereby ensuring the points of intersection being directly superimposed, and, by means of a needle passed through the pricked holes, the marked cloud-points were transferred to the receiver.

This having been done in turn for all the four pictures of the set, the points thus pricked off were joined by inked lines, those obtained from the pair of pictures taken simultaneously being drawn in black ink, and those from the other pair in red, by which a series of parallelograms was formed, equal in number to the number of points selected for treatment.

The black lines or sides of these parallelograms then represented the parallax of the several cloud-points, being proportional in length to the tangent of the angle subtended by the base line at the altitude of the cloud, whilst the red lines forming the other two sides of the quadrilaterals represented on the same scale the drift of the cloud during the interval which elapsed between the taking of the two sets of pictures.

The measurement of these black and red lines provided the means already explained of determining the height of the clouds and the rate of their motion, the direction being given by the inclination of the two lines, of which the black one represented the base.

In dealing with the direction of the drift when thus obtained from positive prints, it has to be remembered that by the printing the right and left of the pictures are transposed, so that the east is on the left and the west on the right in a picture the top of which is directed to the north.

The necessary measurements were made on a scale of millimeters, and the computations carried out by the help of logarithms.

The operations thus described have lately been much abbreviated in various ways. First, it has been found possible to carry out the superposition of the pictures by means of the negatives only, and to work without either employing positives or depending on the identification of a few selected points whose positions were transferred to a receiver.

A frame has been constructed which carries the glass negative plates upon sliders in grooves running in parallel planes, one immediately over the other, but arranged so as to travel at right angles to one another, the lower moving towards and away from the observer, whilst the upper traverses from right to left. A mirror, either a silvered or an opal plate, is employed to reflect the light of the sky upwards to the eye through the negative photograph when the apparatus is placed upon a table in front of a well-lighted window. Stray or diffused light is excluded by placing a box, darkened on its inner surface, over the negatives, and the observer views the combination through a tube fixed perpendicularly upon the top of the box. The two photographs to be compared are placed one in each of the sliding frames, which are first so adjusted that the fiducial lines which follow the direction of the base pass exactly over one another. Next, the bottom or backwards-and-forwards slider is moved until the cloud pictures, say a pair marked A and B, are seen to coincide, and the distance between the intersections of the cross lines on the two plates representing the zenith points, which is the parallax, is then measured by means of a pair of compasses; but a scale could readily be fixed on the slides from which the parallax could be read off without measurement.

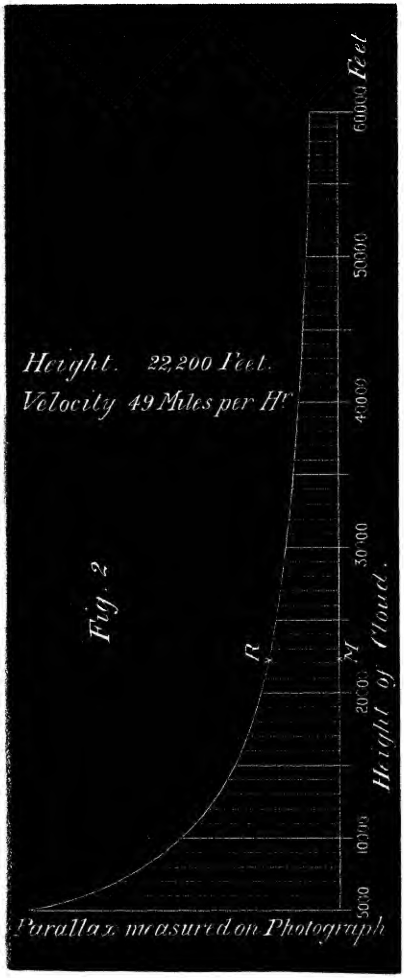
In order to avoid calculations, a standard curve has been drawn (see fig. 2), from which the height of the cloud may at once be graphically determined from the distance between the intersections of the cross lines or parallax of the base as thus measured.

On the axis of abscissæ of this curve are marked off the heights on a scale which makes 2400 feet, the length of the base, equal to the focal distance of the camera, and at regular intervals along this line ordinates are drawn of the length, as measured on the photographs, of the parallax corresponding to the several heights. Through the extremities of these ordinates a curved line is drawn, which gives the locus of the equation

$$h = p \cot \pi,$$

the lengths h and p being both expressed on the scale just mentioned.

The same operations are next performed with pictures A_2 and B_2,



and a second value of the cloud height is obtained, which serves to confirm or modify the first determination.

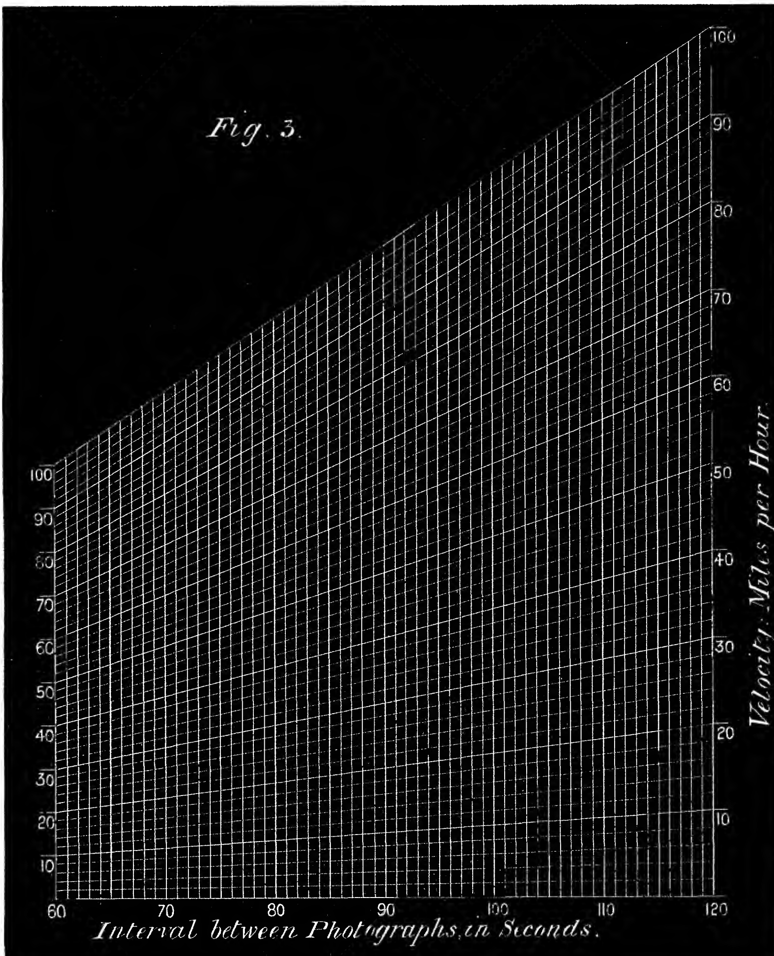
Then pictures A_1 and A_2 are placed in the frame, and the images superimposed and made to coincide as before, but now the distance separating the zenith of the two pictures, which will be termed the drift, will indicate the space the cloud has moved during the interval between the taking of the two pictures; and the angle which the line joining the zeniths makes with the line of base gives the direction in which the drift has taken place.

From the length of the drift measured upon the plates as above, the velocity of motion may easily be obtained by a graphical method.

As before stated, the velocity in miles per hour is

$$V = \frac{\delta}{p} \cdot \frac{\beta}{5280} \cdot \frac{3600}{t''}.$$

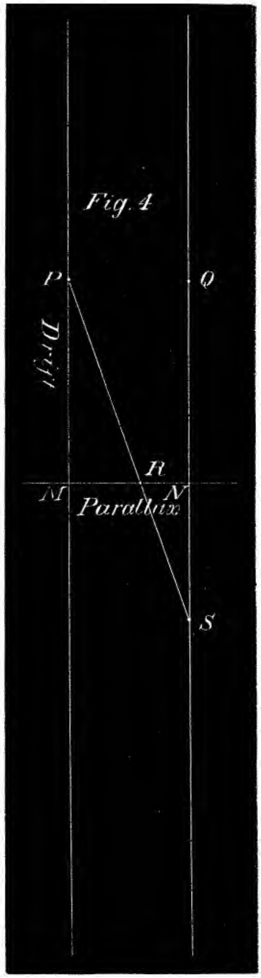
Fig. 3.



To obtain the value of V graphically, proceed as follows:—

Draw a horizontal line on which will be represented equal time-intervals from 0 to 120 seconds, see fig. 3. Erect vertical lines at all the points between 60 and 120 seconds, which will include all the time intervals between the pictures likely to occur in practice. On the first of these verticals mark off any convenient length to represent

1 mile, and divide it into 60 equal parts, and from the zero point on the horizontal line draw radiating lines through the points of division, extending to the vertical at 120 seconds. This constitutes a scale of proportional velocities from 0 to 60 miles per hour, and may be extended to any higher velocity. Next (see fig. 4) draw two parallel



vertical lines at a distance apart equal to the length of the base, 2400 feet, on the scale before assumed to represent 1 mile, and draw a horizontal line intersecting the other two at right angles at points M and N.

Then mark off the length of drift δ upwards on each of the two

vertical lines from M and N at points P and Q; and the length of the parallax p, on the horizontal line from M towards N, at a point R. Join P, R, intersecting the vertical through N at S. Then QS represents the drift on the scale assumed to represent 1 mile. Let this be marked off upwards on the vertical line drawn on the scale of proportional velocities, fig. 3, from the seconds division corresponding to the time interval between the pictures, and the velocity of drift will be indicated by the radiating line nearest to the mark thus made.

The scales above described for the graphical determination of the cloud heights and velocities are engraved and printed on sheets of paper, which, after the computations are completed by their aid, will serve as convenient records of the observations.

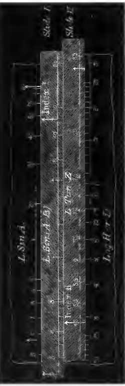
After a little practice, the whole of the processes requisite for these determinations from the glass plate-negatives of a complete set of four pictures will not exceed 20 minutes. Quite sufficient accuracy is ensured, and the labour and risk of error arising from the use of tables is entirely avoided.

Although the cameras now in use only embrace a circle of angular diameter of about 30°, trials have been made with a lens which gives satisfactory pictures of double that extent, which is probably as much as could be desired.

The following is a list of the determinations made during the past year by the methods now described :—

Date.	Height.	Velocity.	Direction.	Surface.	
				Velocity.	Direction.
1890.	miles.	miles.		miles.	
July 10..........	1·29	7·27	N.W.	10	N.W.
„ 16..........	5·20	45·80	S.W.	5	S.W.
	5·47	41·39	S.W.	5	S.W.
„ 16..........	8·39	64·61	S.W.	5	S.W.
	6·34	49·16	S.W.	5	S.W.
August 26.........	2·87	15·19	S.S.E.	15	S.W.
„ 26.........	1·64	20·19	S.S.E.	15	S.W.
„ 29.........	1·97	13·70	W.S.W.	7	N.
„ 29.........	1·93	13·28	W.S.W.	7	N.
September 9.......	6·87	42·40	W.	3	W.S.W.
„ 9.......	6·29	45·18	W.	3	W.S.W.
„ 10.......	7·22	42·00	N.	8	W.N.W.
„ 17.......	2·60	25·90	S.S.W.	10	S.E.
	2·66	19·90	S.S.W.	10	S.E.
„ 17.......	2·87	19·70	S.S.W.	10	S.E.
	2·27	22·00	S.S.W.	10	S.E.
„ 18.......	4·60	54·40	S.W.	16	S.
„ 18.......	4·60	53·10	S.W.	16	S.
„ 23.......	1·72	5·30	S.W.	5	S.
„ 23.......	1·71	6·40	S.W.	5	S.

FIG. 1.




Height . Feet.
Velocity 49 Miles per H^r
Fig. 2
Height of Cloud
Parallax measured on Photograph

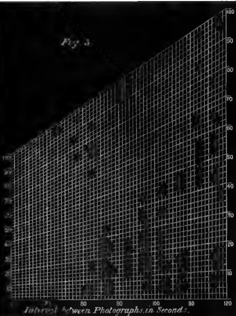


Fig. 5
Velocity, Miles per Hour
10
20
30
40
50
60
70
80
90
100
80
90
100
110
120
Interval between Photographs, in Seconds.

Fig. 4
P
G
Horiz
R
N
Parallax
S